

Chapter 3

Energy and Intermolecular Forces

AS WE HEAT A SUBSTANCE, THE MOLECULES MOVE FASTER AND FASTER. Water in contact with melting ice gets colder: the kinetic energy of the water molecules is transferred to the potential energy of those ice molecules that are separating themselves from the ice crystal and moving into the liquid.

3.1 Intermolecular Forces

We learned in Section 1.2 that temperature is proportional to the average kinetic energy of a system:

$$T \propto \left(\frac{mv^2}{2} \right)_{\text{avg}} . \quad (3.1)$$

where m is particle mass and v is the individual particle velocity. However, this definition is not very enlightening if we do not know the definition of the word “energy.”

So what is energy? The common definition is that energy is the capacity to do *work*. We know from everyday experience that doing work requires effort, at least for some of us.

When we apply a force to an object and move it in the direction of our applied force, we are doing work¹. For example, we do work when we lift a heavy bag, or shovel snow, or hand-saw wood.

¹Energy and work are measured using the same unit, the Joule. One Joule equals the amount of work performed when one Newton of force moves an object one meter. Approximately one Joule of energy is required to lift a stick of butter (100g) from the floor to the table (a distance of about 1 meter).

Energy exists in many forms. To say that the energy of an object is the maximum amount of work it can produce is only partially helpful, because different processes enable differing amounts of work. A ten-liter can of gasoline stored on a high shelf is a simple example. If the shelf breaks, and the can falls to the floor, a small amount of work is done and the floor ends up with a scratch. On the other hand, if the gasoline is poured into a car's gas tank and the heavy car is then driven 100 kilometers, a huge amount of work is produced.

Kinetic energy is one form of mechanical energy and is due to the motion of an object (see Section 1.2).

Another form of mechanical energy is potential energy. Potential energy depends on either (i) the position of an object with respect to other objects or (ii) the deformation of an object. In other words, potential energy depends on the geometry of the system.

The most simple example of potential energy is the potential energy due to gravitational force. In mathematical terms, an object of mass m that lies on the edge of an abyss of a depth h has the potential energy

$$E_P = mgh, \quad (3.2)$$

where $g \approx 10\text{m/s}^2$ is the free-fall acceleration in the gravitational field of Earth. An object has potential energy if it can perform a certain amount of work *in its particular situation*.

A rock that is just about to fall off a cliff has potential energy E_P . When the rock starts falling, the gravitational field of the Earth accelerates it so that when it reaches the bottom it has acquired a certain velocity. The potential energy of the rock at the top of the cliff is transformed into the kinetic energy of the accelerating rock, $mv^2/2$. How can we determine this kinetic energy? Due to energy conservation, the total energy of the rock is the same before and after the fall. At the top of the cliff, before the rock falls, it has only potential energy E_P . At the bottom of the cliff it has only kinetic energy E_K . Due to the law of energy conservation, $E_P = E_K$.

$$mgh = \frac{mv^2}{2}. \quad (3.3)$$

From this equation we can find the velocity of the ball just before it hits the ground: $v = \sqrt{2gh}$.

Potential energy can be negative depending on where you choose the level zero for the potential energy. If we choose level zero to be at the sea level, then at the bottom of the Dead Sea valley in Israel (404 meters below sea level) the potential energy of a

stone weighing one kilogram is $1kg \times (-404m) \times 9.8 \frac{m}{sec^2} \approx -4000$ Joules. This means that 4000 Joules of work are required to bring the stone up to Mediterranean sea level, where the potential energy is defined to be zero.

Another form of potential energy is the energy stored in a “deformed” object such as a compressed spring or a drawn bow just before the release of an arrow. When we draw a bow we apply force (and perform work) to pull back the bow-string. This work is stored in the bow in the form of potential energy. When we release the string, it performs work as it rapidly accelerates the arrow forward. The potential energy of the bow is transformed into the kinetic energy of the arrow.

Q3.1: What happen with the kinetic and potential energy of the arrow as the arrow flies up? Clue: The arrow flies in the gravitational field of the Earth

How can the body of the bow store energy? The body stores energy as a result of the internal forces (both attractive and repulsive) between its atoms and molecules. These forces are caused by the electrical charges of the of the bow’s molecules and atoms. These forces stores potential energy in the same way as the gravitational force stores potential energy of the rock in the above example. The intermolecular forces between the bow’s molecules—molecules that attract and repulse each other—store the energy.

Scientists have discovered that these forces, derived from the intermolecular potential energy, are affected by the distance between the molecules. At very large distances, the forces are so small that essentially the molecules do not interact. As the molecules move closer to each other, the interactions of the nuclei and electrons cause an attraction to develop. When the distance between molecules becomes very small, however, the repulsion between electron clouds of the molecules begin to dominate and the molecules begin to repel each other.

These forces are illustrated in the graph of potential energy E_P versus distance separating molecules r (see Figure 3.1). We treat this graph as a imaginary roller coaster. The height of the graph h determines the potential energy of the pair of molecules in exactly the same way as the height of the ball on the roller coaster determines its potential energy. The steeper the slope of the graph, the larger the attractive or repulsive force.

Note that at the lowest point in the graph, the ball has a negative potential energy of -1 , corresponding to a position at the bottom of the “Dead Sea valley”. The flat part

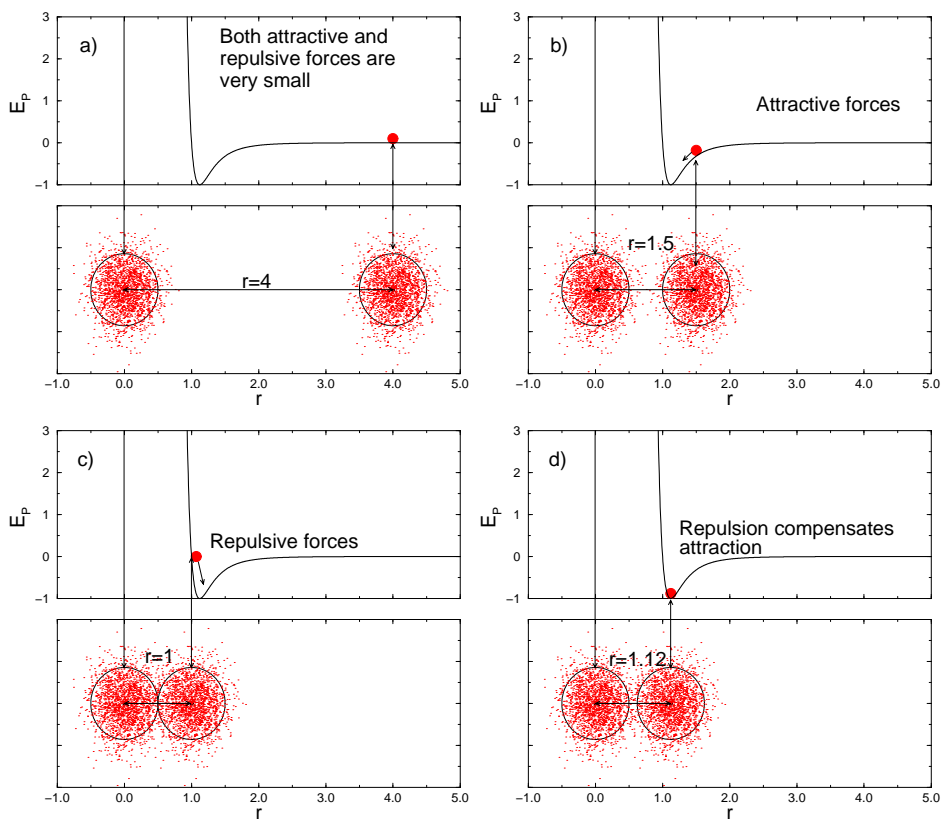


Figure 3.1: Potential energy E_p of intermolecular forces as function of the intermolecular distance r . Each pair of graphs illustrates the interaction of two atoms of noble gases at different distances from each other. The atoms are shown as negatively charged electron clouds with small circles at the center, indicating positively charged nuclei. The two large circles show effective atomic sizes, which correspond to the minimal distance, atoms can approach each other during a collision at low temperature. Above the atoms we show the potential energy landscape of the pair of atoms. The small ball indicates the analogy with the gravitational potential field. The ball in this landscape has the same potential energy as the pair of atoms. The forces acting on the atoms are proportional to *the slope* of the landscape at the ball's location.

of the graph for a very large r corresponds to “Mediterranean Sea level”.

- CASE 1: At very large distances the graph is completely flat as shown in Figure 3.1a and our ball does not move. In molecular terms, the molecules neither attract nor repel.
- CASE 2: At distances closer than three molecular diameters as shown in Figure 3.1b, our ball rolls left down to the lower level. In this case, the molecules are still separated by relatively large distances and are weakly attracted to each other.
- CASE 3: At very small distances, shown in Figure 3.1c, our ball moves quickly to the right due to the steep slope indicating that the molecules repel each other.
- CASE 4: Finally, if the ball is placed at the bottom of the curve shown in Figure 3.1d, our ball does not move at all. This distance corresponds to the minimum potential energy, the configuration at which attractive and repulsive forces between molecules balance each other. Molecules in this configuration have no *net* force.

We can also learn from figure 3.1 why substances at different temperatures exist in different states: gaseous, liquid and solid. Recalling that temperature is a measure of the average kinetic energy of molecular and atomic motion, we can conclude that at low temperatures, molecules are trapped in a relatively rigid structure forming a crystal lattice. The molecules position themselves at a distance that minimizes their potential energy, they sit in the “Dead Sea valley’s” of the imaginary potential energy landscape. They have kinetic energies that are much smaller than the potential energy barrier they need to overcome if they are going to escape the relatively rigid solid structure (see figure 3.2).

If we put a ball at the lowest point on our imaginary roller coaster and kick it gently, it will move back and forth near this lowest point, but never manage to escape. In the same way, molecules in a crystalline lattice vibrate near their minimal potential energy positions.

As we heat our substance, the molecules move faster and faster. Occasionally some of them acquire a kinetic energy larger than the potential energy barrier and break away. Returning to our roller coaster, if we kick our ball hard enough, it will escape the bottom level of our graph. Its kinetic energy decreases by the amount of potential energy it gains as it climbs up the hill. We know that water in contact with melting ice gets colder: the kinetic energy of the water molecules is transferred to the potential energy of those ice molecules that are separating themselves from the ice crystal and moving into the liquid.

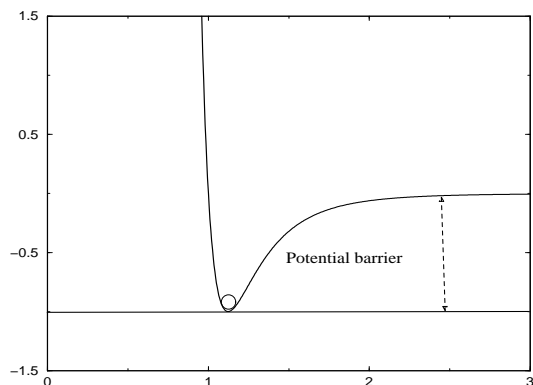


Figure 3.2: Potential energy of molecule in crystal lattice is at a minimum. Potential barrier must be overcome if molecule is to leave the solid state.

At very high temperatures, all the molecules separate from each other. If we kick our ball very hard, it rolls away from the potential minimum, reaches the plateau part of the graph, and continues to roll forever—or would, were it not for the friction forces that eventually slow it down. In the same way, water molecules leave the surface of boiling water and move away at high velocities in the form of water vapor.

BEGIN ACTIVITY

SimuLab 24: Intermolecular Forces**Your objective is to:**

Recognize the forces that acts between particles of gas and relate these forces to the macroscopic behavior of the substance.

You will be able to:

Explore the microscopic interactions of two noble gas atoms.

Study how the forces acting between atoms of noble gases depend on the distance between the two atoms.

Explore the relation between the internal potential energy and the interatomic forces.

Test if the law of conservation of energy is satisfied.

Relate temperature and strength of intermolecular forces to the phase changes.

Make two copies of the following table. Do not fill data in the column Distance in the second copy.

No. of Experiment	Distance	Particle's Behavior	Kinetic Energy	Potential Energy	Total Energy	Final State
1	3.5					
2	2.0					
3	0.9					
4	1.2					

Using Fig. 3.1 make your predictions, in the following experiments, concerning two particles, whose centers are separated by:

- 1) more than 3 particle diameters

- 2) approximately 2 particle diameters
- 3) less than 1 particle diameter
- 4) 1.2 particle diameters

Fill your predictions in the first copy of the table using the following possible choices:

Particle's Behavior: Stay in place (A), Attract (B) or Repulse (C)

Kinetic Energy: Stays constant (A), Increases (B) or Decreases (C)

Potential Energy : Stays constant (A), Decreases (B) or Increases (C)

Total Energy : Stays constant (A), Decreases (B) or Increases (C)

Final State : Particles stay apart (A), Oscilate near equilibrium position (B), Move freely in the entire box (C) or Stay close to each other in fixed position (D)

Now you will test your predictions by performing the SimuLab and recording your observations in the second copy of the table.

1. Open **SMD**, select file **Intermolecular** in the **Energy** folder.

You see a single particle in the center of the particle screen.

2. Press **Start**

The particle is completely motionless. Watch the graph of the energies at the right part of the simulation window. It shows kinetic, potential, and total energy of the particle as functions of time by the red, blue, and black lines, respectively. If the red or blue lines are invisible, it means that they exactly coincide with the black line.

3. Press **Pause**.

The potential energy of a single particle is defined to be zero, because our particle does not interact with any other particles or its surroundings.

Q3.2: What is the kinetic energy of the particle? Explain your answer.

Q3.3: What is the total energy of the system?

4. **Reset Experiment** from the **File** menu.
5. Select **Particles** from the **Edit** menu. The dialog box **Edit Particles** appears. Select **Add Particle G** and click mouse inside the particle box near the edge.
6. Press **Start**, wait approximately 5 time units and press **Pause**. Using the graph, record your observations in the table and compare them with your prediction.

You will be placing another particle at various distances from the existing atom and study their interaction.

A new green particle will appear.

Make your observation of the particle behavior and the behavior of the kinetic, potential, and total energies.

7. **Reset Experiment** from the **File** menu. Select **Particles** from the **Edit** menu. The dialog box **Edit Particles** appears. Select **Add Particle G** and place the center of the second particle at the distance of approximately 2 particle diameters from the center of the first one. Repeat Step 6.
8. **Reset Experiment** from the **File** menu. Select **Particles** from the **Edit** menu. The dialog box **Edit Particles** appears. Select **Add Particle G** and place the center of the second particle at the distance of approximately 0.9 particle diameters from the center of the first one. Repeat Step 6.
9. **Reset Experiment** from the **File** menu. Select **Particles** from the **Edit** menu. The dialog box **Edit Particles** appears. Select **Add Particle G** and place the center of the second particle at the distance of approximately 1.2 particle diameters from the center of the first one. Repeat Step 6.

The edges of the particles should touch each other. Our computer model does not allow particles to be less than 0.8 particle diameters from each other. So try to click the mouse several times, slowly moving the cursor away from the center of the existing particle until you succeed in placing the new particle at the desired distance.

There should be a small gap between the edges of the particles.

Q3.4: Explain the observed changes in potential and kinetic energies.

Q3.5: Relate the behavior of the particles to the behavior of the particles in a crystal.

10. Press **Pause**. Using **Temperature** scrollbar, increase the value of Temperature to 0.4. Press **Start**.

You will study the effect of temperature on the particle behavior. The temperature scrollbar indicates the average kinetic energy of the particles at given time. By increasing this value, you are increasing the kinetic energies of both particles by the same amount. The graph of energies indicates the average kinetic energy, average potential energy, and average total energy of each particle. You can precisely determine the values by pressing the mouse at a given position on the graph.

Q3.6: This case corresponds to a crystal melting. Describe the particle behavior in terms of potential energy graph. Clue: See Fig. 3.2.

11. Press **Pause**. Using the **Temperature** scrollbar, increase the value of Temperature to 0.5. Press **Start**.

Predict the particle behavior. Watch the behavior of the particles and determine if your prediction is accurate.

Q3.7: This case corresponds to evaporation. Describe the particle behavior in terms of potential energy graph. Clue: See Fig. 3.2.

3.2 Kinetic and Potential Energy of Particles

BEGIN ACTIVITY

SimuLab 26: Kinetic and Potential Energies of Particles in Gas State

Your objective is to:

Investigate the correlation between the kinetic, potential energies and temperature as gas particles move and collide.

You will be able to:

Define potential energy and kinetic energy and give an example of each.

Discuss the relationship among potential energy, kinetic energy, and total energy before, during, and after a two-particle collision at a given temperature.

State the relationship between the average kinetic energy of randomly moving particles and the temperature of the system.

Describe what happens to the speed of particles in a system as the temperature is raised.

1. Open **SMD**, select **Experiment25** in the **Energy** folder. Press **Start**. To speed up the simulations set **Iterations between Displays** to 5

You are visualizing a low-density gas, see Fig. 3.3. There is no exchange of energy with the surroundings (i.e. the system is thermally isolated). Thus the total energy of the system is conserved. Each gaseous particle moves along a straight line until it collides with another particle or with the container walls.

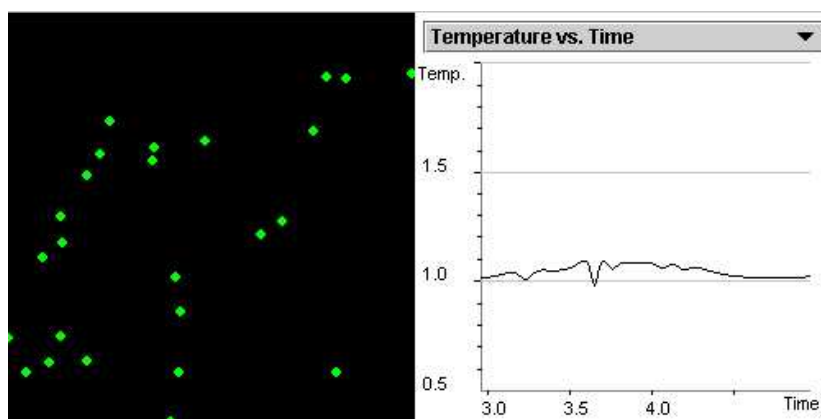


Figure 3.3: You are visualizing 25 green gas particles at temperature $T = 1$. The temperature $T = 1$ is far above the boiling point of the substance.

Observe the graph **Temperature vs. Time** (see Fig. 3.3).

The temperature T reading below the screen is an exact computation of the average kinetic energy, E_k of a particle in the system, $T = \left(\frac{mv^2}{2}\right)_{\text{avg}}$. The temperature is calculated at every simulation step: the program calculates the kinetic energy $mv^2/2$ for every particle, adds them together and divides by the total number of particles.

Q3.8: Describe the graph and explain why the temperature is not constant?

2. **Pause** the simulation. Using the scroll-bar, increase the temperature from the current value $T = 1.0$ to a new value $T = 4.0$ and press **Start**.

Q3.9: Do the molecules move faster or slower? Explain.

3. In order to visualize the change in the kinetic energy of the individual particles, switch the menu **Display Particles by** to **Absolute Kinetic Energies** as shown in Fig. 3.4.

Some of the particles are violet, blue, green, yellow and red. The color of each particle indicates the amount of kinetic energy it has as you can see from the **Spectrum of Kinetic Energies**. The violet particles have the highest kinetic energy (move at the highest speed), then come the blues, then green, then yellow, and then red, which have the lowest kinetic energy (move at the lowest speed). When they collide, their colors change.

Q3.10: What do the changing colors indicate about the particle's kinetic energies as they collide?

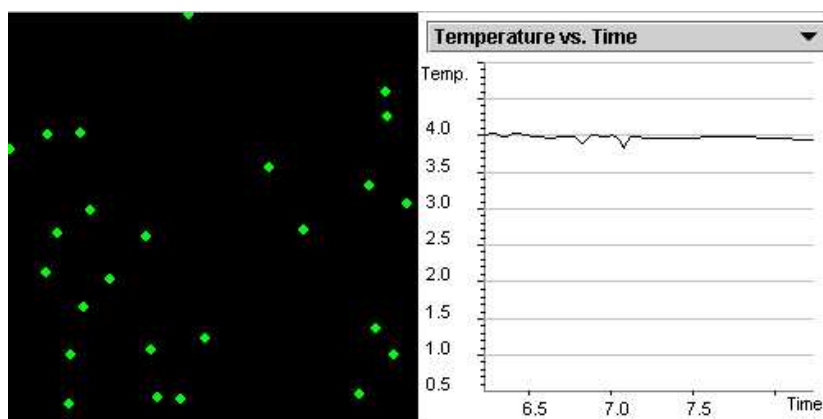


Figure 3.4: A snapshot of the application screen representing the same gas as in Fig. 3.3, but at temperature 4. The color of each particle indicates its kinetic energy.

4. Switch the menu **Display Particles by** to **Potential energy**.

The color coding now indicates the value of each particle's *potential* energy as you can see in the **Spectrum of Potential Energies**. Most of the particles are so far away from each other that there is almost no interaction between them. Their potential energy is assigned a value of zero and colored light blue. The particles that are close to each other have a negative potential energy and are colored green.

5. Go to **Options – Select Delay** and select Short Delay.

You are selecting a short delay to better see the changes of potential energy of colliding particles. When two particles collide, the potential energy increases and the kinetic energy decreases. The total energy of the interaction remains constant. The increase in potential energy of the two particles is indicated by a change of color to dark blue and violet. The decrease in kinetic energy of the two particles is indicated by the dip in temperature on the temperature graph.

6. Switch the **Graph to Energies**. Turn off the delay.

On the energy graph the average kinetic energy of the particles is indicated by the red line, the average total energy of the particles is indicated by the black line, and the average potential energy of the particles is indicated by the blue line.

The total energy is constant as is reflected in the flatness of the black line (see Fig. 3.5).

Q3.11: Try to explain the peaks in the graph of kinetic and potential energies. Why are they complementary? Clue: Watch if they correspond to the moment of a collision

Q3.12: Why does the total energy of the system—which is the sum of its kinetic and potential energy—remains constant?

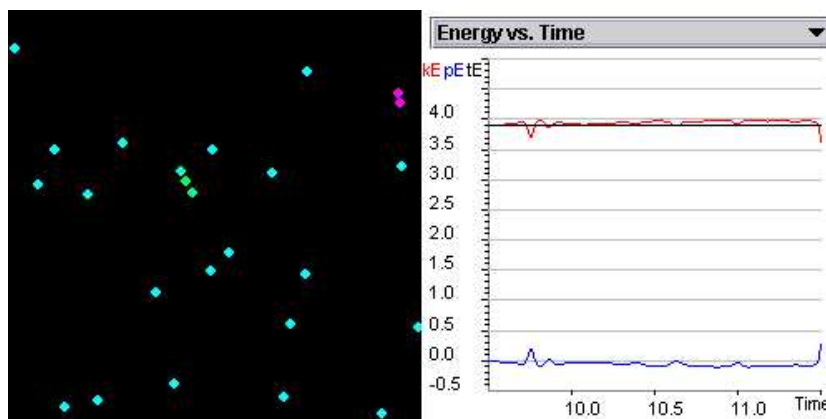


Figure 3.5: The same system as in Fig. 3.4. The color of each particle now indicates its potential energy. A pair of colliding particles with a positive potential energy appears in bright magenta. The graph showing potential energy vs. time (bottom curve) indicates the maximum at the time of collision (Time ≈ 9.75). The graph showing kinetic energy (top curve) indicates the minimum at that point. The fluctuations of kinetic and potential energies are, in fact, complementary (in the sense that peaks in potential energy correspond to dips in kinetic energy, and vice versa)—and the total energy of the system, indicated by a straight black line, is constant.

BEGIN ACTIVITY

SimuLab 28: Kinetic and Potential Energies of Particles in Liquid State

Your objective is to:

Recognize the difference between a gas and a liquid in terms of the energies of the particles.

You will be able to:

Differentiate among the liquid and gas state in terms of average kinetic energy and the average potential energy of the particles.

Contrast the potential energy of a molecule in the center of a droplet with that on the edge of the droplet.

State the relationship between the trajectory of a particle and its potential energy.

Explain the release of latent heat when a gas condenses.

1. Open **SMD**, select **Experiment 1** in the preset experiments in **Energy** folder and press **Start**. Make sure that the **Iterations between Displays** are 5.

2. **Pause** the simulation and reduce the temperature to 0.01. Press **Start**.

You are visualizing 144 particles of a high-density gas. There is no exchange of energy with the surroundings (the system is thermally isolated) and thus the total energy of the system is conserved.

At first the particles almost stop, but then they start to accelerate toward each other, and form little droplets. The formation of droplets is called condensation and occurs naturally in clouds.

Q3.13: Do you expect a particle in the center of a droplet to have the same or different potential energy when compared to a particle at the edge of the droplet. Explain your reasoning.

3. In order to speed up the simulations change **Iteration between Displays** to 100. Press **Pause** and switch **Display Particles by** to **Potential Energy** and press **Start**.

The temperature steadily increases until it levels out. Notice that the droplets break apart and that the color of particles in the middle of the droplets changes to yellow (i.e. these particles have a relatively low potential energy).

Q3.14: When you lowered the temperature of the system to 0.01 what happened? Explain the rise in temperature you observe.

The increase of temperature—the “release of latent heat”—during condensation is a well-known phenomenon. Latent heat of condensation is the increase in the kinetic energy of thermal motion of all the particles in the system caused by a decrease in the potential energy of the attracting particles (droplets).

If you continue the simulation long enough (50-60 unit times), the temperature will rise sufficiently that the particles in the droplets will have enough kinetic energy to break away and travel through the surrounding gas (see Fig. 3.6). The droplets will stop growing and will continually break apart and reform.

4. Switch the **Graph** to **Energies**. If more than 50 time units elapsed, **Reset** the experiment and repeat step 2.

Notice how, during the experiment, the average potential energy decreases while the average kinetic energy has increased.

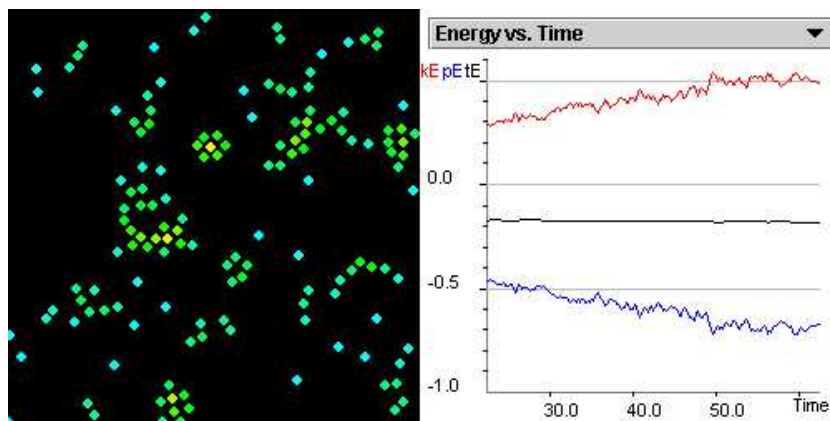


Figure 3.6: The system showing the gas near its condensation point. Little droplets of liquid form, but almost immediately break apart. The color coding indicates the potential energy. The particles in the droplets are green and yellow, indicating that they have relatively low potential energy.

Q3.15: Explain why during condensation, in a thermally isolated system, many small droplets form, but they do not coalesce to form a single droplet.

5. **Reset** the experiment. Switch **Display Particles** by to **Potential Energy**. Switch the **Graph** to **Energies** and set the temperature to 0.4. This temperature is below the condensation point. Put the **Heat Bath** on and press **Start**. Watch the system for 200 times units.

In order to simulate a gas-liquid transition, we must cool the system further. In order to achieve this, the latent heat of condensation that is produced must be dissipated into the larger surrounding system. This is done on the computer by putting the **Heat Bath** on. Now the system will exchange energy with the surroundings. See how the droplets form steadily.

Q3.16: What happens to the energies, E_k , E_p and E_T of the system?

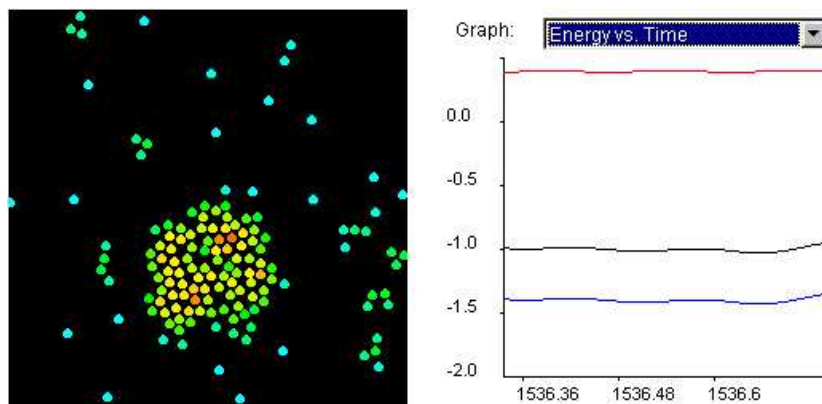


Figure 3.7: The system is at constant temperature of $T = 0.4$. The graph shows average kinetic energy (top line), total energy (middle line), and potential energy (bottom line), all with virtually no fluctuation. Almost all the gas condenses into liquid droplets that are in equilibrium with the surrounding gas, which is of extremely low density. Some of the particles escape from the droplets and some coalesce with them. The color coding indicates the potential energy of each particle. Note that the particles in the middle of the droplet have the lowest potential energy. The time on the graph indicates the time elapsed since the beginning of condensation, i.e., since the temperature was lowered from $T = 1$ to $T = 0.4$.

6. Because the condensation process requires a significant amount of computer time, we recommend opening the **Experiment1a** file. Switch the graph to potential energies.

This starts the experiment at the stage where almost all the particles have coalesced into large droplets (see Fig. 3.7).

Q3.17: Watch the colors of the particles in the big droplet (see Fig. 3.7). In the center they turn to orange and yellow while on the edges they remain green.

Explain why? Clue: how many neighbors do the particles in the center have compared to those on the edge?

Notice that there are still free particles (light blue) in the system with almost zero potential energy. These particles sometimes leave the droplet and sometimes join with it. These particles represent a gas in equilibrium with a liquid: the rate in which the particles leave the droplet is the same as the rate as which they join the droplet.

Q3.18: Explain the changes you see in terms of potential energy of particles at the moment when a particle leaves the droplet and when it joins the droplet.

7. Switch **Display Particles** by to **Trajectories** and press **Start**.

The particles in the droplet move along curved lines, while in the gas they move along straight lines.

Q3.19: How do you explain these trajectories in terms of the potential energies of the particles?

SimuLab 30: Sublimation, Deposition, and Triple Point.**Your objective is to:**

Recognize sublimation, deposition and triple point from a microscopic point of view.

You will be able to:

Describe the process of deposition and explain it in terms of potential energy.

Describe the process of sublimation and explain it in terms of energy.

Compare and explain the potential energies of particles that exist at the triple point.

Describe molecular motion at the triple point.

1. Open **SMD**, select **Experiment 1a** in the **Energy** folder, set **Iterations between Displays** to 500 and press **Start**.
2. Switch **Display Particles by** to **Potential Energy**. Pause the simulation. Select **Take a Snapshot – Screen**. When the dialog box with the **Title of the Picture** appears type in: “Liquid” and press **Ok**.
3. Now drop the temperature to $T = 0.3$.

The experiment starts at the stage where almost all the particles have coalesced into large droplets. The **Heat Bath** is on. You see 144 particles in contact with a thermal bath whose temperature is $T = 0.4$.

This temperature is below the freezing temperature of the substance.

4. Press **Start**.

After 100 time units, pause the simulation.

Watch the changes in the colour representing the potential energy of the particles.

The particles in the gas start to form little “snowflakes” that eventually merge with the large crystal. This phenomenon is called *deposition*.

Q3.20: What happens to the droplet?

5. Select **Take a Snapshot** –
Screen. When the dialog box with the **Title of the Picture** appears type in: “Solid” and press **Ok**.

Q3.21: Now compare the snapshots in the two phases. What differences do you see? Explain.

Q3.22: What happens to the potential energy of the system when you drop the temperature to 0.3?

Q3.23: Are there any particles not in the solid state? If yes describe them.

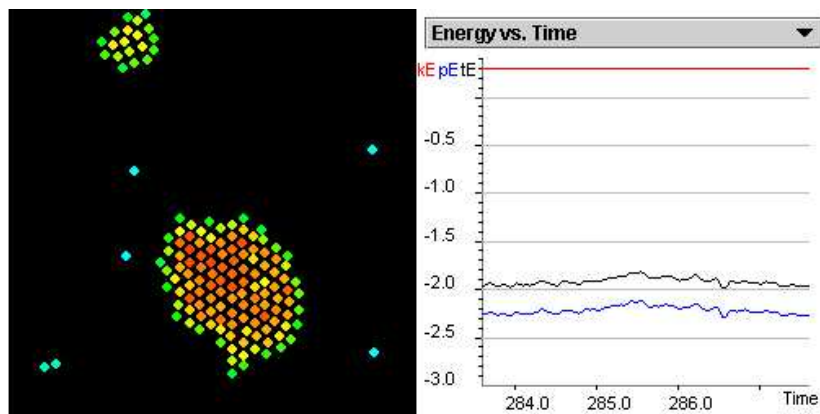


Figure 3.8: The system at temperature $T = 0.3$. The droplet is frozen into a “triangular” crystal. The time on the graph indicates the time elapsed since the beginning of crystallization, i.e., since the temperature was lowered from $T = 0.4$ to $T = 0.3$. Next to the crystal is a little “snowflake” that will eventually coalesce with the crystal. The few gaseous particles are in equilibrium with the crystal.

6. Deposition requires a significant amount of computer time to simulate. We recommend opening the **Experiment1b** file in order to skip the earlier stages of the process and press **Start**. Switch **Display Particles** by to **Potential Energies**.

You see some gas molecules surrounding the crystal. The gas has much lower density than before. The gas particles separate from and rejoin the crystal. This happens to snow in very cold weather—it gradually disappears, moving directly from the crystalline snowflake state into the water vapor state without ever passing through the liquid water state. The same thing happens to solid carbon dioxide (CO_2 , “dry ice”) when it turn into a gas. This phenomenon is called *sublimation*.

7. Set the temperature to $T = 0.33$ which is the temperature of the *triple point*. At this temperature all three phases—solid, liquid, and gas—coexist. Press **Start**.

Q3.24: What happens to the crystal?

8. Switch **Display Particles by** to **Trajectories** in order to see the movement of particles in the three states of matter.

Q3.25: Watching the trajectories of the particles identify the three states of matter. How can you distinguish gas, liquid and solid in terms of the particle trajectories?

9. Set temperature to $T = 0.4$. Watch the changes in the crystal. Set temperature to $T = 1.0$. Describe the changes in the system.
10. Switch **Display Particles by** to **Absolute Kinetic Energy**. Watch the color of the particles.

Q3.26: Do all the particles move at the same speed? Explain what you see.